R1 The burden of biofouling at sea

What burden does the fouling of marine life place on ships and fishing nets, and how large is it?

Readers	Ship owners, shipyards, staff of fishery cooperatives and others without specialist knowledge, who want to know where fuel costs and the labour of upkeep come from.
Takeaways	1. When the underwater part of a ship becomes fouled, the ship uses extra fuel. How much more depends heavily on the conditions. International emissions calculations assume a uniform 9%, and calculations for large, fast cargo ships give several tens of percent at a given point in time, even for a thin slime layer or thin barnacles. 2. Today's measures, such as paint, hull cleaning, propeller polishing and maintenance with the ship taken out of the water, are effective. However, they have limits: how long the effect lasts, the substances released by cleaning, and regulation of the ingredients. 3. When fishing nets become fouled, cleaning and replacing them takes labour and time. However, there are few figures on the cost, and almost no figures for Hiroshima and the Seto Inland Sea.
After reading	For your own boats and nets, keep the fuel used and the dates of cleaning, repainting and replacement in the same record.

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1. Key points

- When the underwater part of a ship becomes fouled, the ship uses extra fuel. How much more depends heavily on the conditions. International emissions calculations assume a uniform 9%, and calculations for large, fast cargo ships give several tens of percent at a given point in time, even for a thin slime layer or thin barnacles. [S1, S2]
- Today's measures, such as paint, hull cleaning, propeller polishing and maintenance with the ship taken out of the water, are effective. However, they have limits: how long the effect lasts, the substances released by cleaning, and regulation of the ingredients. [S3, S4]
- When fishing nets become fouled, cleaning and replacing them takes labour and time. However, there are few figures on the cost, and almost no figures for Hiroshima and the Seto Inland Sea. [S5, S6]

2. What is happening

World and Japan: ship fuel

When the underwater part of a ship becomes fouled, the ship uses extra fuel. This is because the resistance of the water increases, and more power (the force the engine produces to move the ship forward) is needed to reach the same speed. [S7] The biofouling guidelines of the IMO (International Maritime Organization) are aimed at measures against non-native species, but they also state that fuel efficiency may improve. [S4]

How much fuel use increases varies greatly with the fouling, the ship and the speed (Table 1). The large values are calculations for a given point in time in a report by GloFouling (an international project on biofouling measures by the IMO and others), which assumed that fouling was spread uniformly over large ships 175–230 m long travelling at 16–24 knots (1 knot is about 1.85 km/h). [S2] In a calculation for a US Navy destroyer (one ship class), annual fuel use increased by about 10% with typical fouling under continued use of copper-based paint and regular in-water cleaning. The roughness of a freshly applied coating alone, compared with a smooth hull, gave 1.4%. [S7]

The heavier the fouling, the more the required power increases. In a calculation by the same researcher (Schultz) for a US Navy frigate (one ship class), the power required at 15 knots increased, compared with a smooth hull, by about 2% with a freshly applied coating, by about 21% with a heavy slime layer, and by about 86% with heavy calcareous fouling (a state in which organisms with calcareous shells, such as barnacles, form a thick covering). The calculation assumes that fouling is spread uniformly over the whole hull, and the author himself states that this is not usually the case on real ships. These are values for power, not fuel (for the difference between power and fuel, see chapter 5). [S7]

Table 1 Increase in fuel use and power due to fouling (international sources)

Source	Conditions	Increase	What quantity, and type of value
IMO study (2020) [S1]	Calculation of world emissions. Applied uniformly to all ship types, including fishing vessels	+9%	Resistance and fuel. Assumption (carried over from the 2014 study, with no explanation of the basis)
Schultz et al. (2011) [S7]	One class of US Navy destroyer (gas turbine propulsion, waterline length [the length of the ship at the level of the water surface] 142 m). Typical fouling (heavy slime layer), judged from 320 records of diver inspections (2004–2006), assumed to be spread uniformly over the whole hull. State under continued use of copper-based paint and regular in-water cleaning	+10.3% (upper-bound scenario [a state with small hard fouling mixed in] +20.4%)	Annual fuel. Calculation
Schultz (2007) [S7]	One class of US Navy frigate (waterline length 124 m), 15 knots. Fouling assumed to be spread uniformly over the whole hull	Freshly applied coating +2%, deteriorated coating or light slime layer +11%, heavy slime layer +21%, small calcareous fouling or seaweed +35%, medium calcareous fouling +54%, heavy calcareous fouling +86%	Required power (compared with a smooth hull). Calculation
GloFouling (2022) [S2]	Cargo ships of 175–230 m, 16–24 knots. Slime layer 0.5 mm thick on up to 50% of the hull	+25–30%	Fuel at a given point in time (assumed proportional to power). Calculation
Same as above [S2]	230 m container ship, 24 knots. 5 mm barnacles on 20% of the hull	Up to +60%	Same as above

Note: GloFouling states that it is very difficult to derive from these results the share of the world's ship emissions that is due to biofouling. For world values on small fishing boats, there are an estimate in guidance from the FAO (Food and Agriculture Organization of the United Nations) (in the tropics and without paint to prevent fouling, +7% after 1 month and +44% after half a year; no source, sample or method stated) and a 1982 trial of one boat by the same author (a badly fouled 28-foot [about 8.5 m] fishing boat in Sri Lanka, whose fuel use per nautical mile [about 1.85 km] fell by about 35% after cleaning; whether it was a typical boat is unknown) [S8]. The only actual measurement for a fishing boat in Japan is one case in Okayama Prefecture.

On real ships, too, fuel use falls after cleaning. A study estimated the change in fuel use before and after cleaning by two statistical methods, using the 2012–2016 operating records (the noon reports that ships send every day) and weather data of 8 medium-sized crude oil tankers of the same type (Aframax type). It found a fall of about 9% after in-water hull cleaning and of about 17% after dry-docking (taking a ship out of the water for inspection and repair) (abstract only checked). [S3] The effect was larger on laden voyages than on voyages without cargo. [S3] If cleaning is done when the ship is fouled, this is the effect of one cleaning, not the average penalty. Also, since dry-docking includes repainting and other work, the figure of about 17% is not the effect of cleaning alone (both are this paper's interpretation).

World and Japan: maintenance and dry-docking, non-native species

Under the Ordinance for Enforcement of the Ship Safety Act (Article 18), most ships holding a 5-year inspection certificate have the outside of the hull, including the bottom, inspected twice in 5 years (the periodic inspection, and the Type 1 intermediate inspection in months 21–39; for ships 24 m or more in length engaged in international voyages [excluding ships used only for fishing], the intermediate inspection is a Type 3 intermediate inspection within 36 months). Both require the ship to be taken out of the water, or preparations that the national government recognises as equivalent. For passenger ships of 5 tons or more (a ship's tonnage is a measure of size based on volume, not weight), high-speed craft and others, this is every year. [S9] Small ships under 20 tons (other than passenger ships) undergo a periodic inspection every 6 years and an inspection midway (in months 33–39), and whether they are inspected out of the water depends on the type of ship and the waters in which it sails. Registered fishing boats under 20 tons that are used only for fishing and only in the sea within 12 nautical miles (about 22 km) of the coast and in rivers, lakes and the like are exempt from inspection. Because there is no inspection, this law sets no rule for such boats on when they are to be taken out of the water. [S9, S10]

The national government has published a 2005 trial calculation that reducing the dry-docking of domestic passenger ships from every year to about every 2 years would lower operating costs by several percent for long-distance ferries and others. In the trial calculation by a study committee of the Shipbuilding Research Association of Japan, published by the Ministry of Land, Infrastructure, Transport and Tourism in 2005, extending the interval between dry-dock inspections of coastal passenger ships (passenger ships that sail within Japan) from every year to about 2 years was found to cut operating costs by about 4–5% for long-distance ferries and others (because repair costs and the loss from being unable to operate during dry-docking are reduced; on the assumption that roughly one third of the 50 long-distance ferries use the scheme, a little over 1 billion yen a year for the industry as a whole). It is a 2005 trial calculation and a value for the whole cost of dry-docking, not the cost of biofouling measures alone. [S28]

Repair costs in the fishing-boat fisheries (repairs to hulls, engines, fishing gear and so on) are 8–10% of fishing expenditure on the national average. In the Ministry of Agriculture, Forestry and Fisheries' 2025 (Reiwa 7) statistical survey of fishery management, the fishing expenditure (expenditure on fishing) of individual (household) management entities in the fishing-boat fisheries (a fishery management entity is a household or company that engages in fishing or aquaculture for sale; individual management entities are the households among them, here those that are full-time and Type 1 part-time, whose income from their own fishery is larger

than their other income) averaged 6.44 million yen per entity in 2025, of which repair costs were 8.0%. For company management entities (the companies among the fishery management entities, whose powered fishing boats in use total 10 tons or more), the figure was 10.1% in fiscal 2025. The repair costs of individual management entities include only repairs commissioned from shipyards, manufacturers and the like, and do not include cleaning and painting done by the owners themselves. For both values, the share for biofouling measures is not known. They are national averages, not values for Hiroshima and the Seto Inland Sea. [S29, S13]

Biofouling on ships is one of the pathways that carry non-native species, but in reality direct evidence is scarce. There is a literature-based estimate (2004) that 44% of the 25 marine species unintentionally introduced into Japan came by hull fouling, including sea chests (seawater intakes), while in the world records, direct evidence existed for 42 of the 1,468 cases in which biofouling was considered a candidate pathway. [S11]

World and Japan: fishing nets and aquaculture

When fishing nets become fouled, cleaning and replacing them takes labour and time. According to a review article, heavy fouling can reduce the flow of water through a net pen (a net enclosure in which fish are kept) to less than half (a value from one 1989 master's thesis), and there are also records of fish dying from lack of oxygen. [S12] The force that a fouled net receives from the current is said to be possibly 12.5 times that on a clean net (a value from a 1970 design guidance cited by the review article, with no method stated). In a 2018 study, the value is up to 10 times. [S12] A recent study states that the volume of a net pen decreases by up to 40%. [S5]

In salmon aquaculture in the heavily fouled waters of Norway, nets are said to be washed in the water once every 2 weeks, or more often if fouling is heavy. The outsourcing cost for one 18-month production cycle with 8 net pens (50 m in diameter) is estimated at about 420,000 US dollars for uncoated nets (25 washes) and about 490,000 US dollars for coated nets (15 washes plus coating) (a rough estimate from around 2020 based on interviews). The washing also includes a portion done for the sake of the "cleaner fish" that eat parasites, and the authors state that this may be the largest factor determining the number of washes; it is not the cost of biofouling alone. [S5]

Figures for Japan are few and old. In a trial on set nets (nets left in place at a fixed location) in Sagami Bay, hydroids (small organisms related to jellyfish and sea anemones) attached to test netting without antifouling treatment at 8 kg or more per square metre in 3 weeks (wet weight; one site off Odawara at a water depth of 5 m, summer 1995). Cleaning or replacement every 7–10 days was considered desirable in summer. [S6] The same report states that many set-net management entities are small family businesses in which elderly people work, and that frequent replacement and cleaning of nets is a heavy burden in labour and cost. [S6]

The number of people working in fisheries nationwide is falling. In the Ministry of Agriculture, Forestry and Fisheries' survey of trends in fishery structure, fishery workers (people aged 15 or over who did fishery work at sea on 30 days or more in a year) as of 1 November 2025 were estimated at 109,820, down 5,000 (4.4%) from the previous year. This is an estimate (approximate figure) from a sample survey, and it cannot be compared directly with the values for the years of the Census of Fisheries, which surveys all entities. It is a national value, not a value for Hiroshima. We found no source showing a relationship between this decrease and the burden of biofouling. [S45]

Region (Hiroshima and the Seto Inland Sea): ships and fisheries

Almost all fishing boats in Hiroshima Prefecture are small. Of the 2,905 fishing boats in 2023, 1,982 were powered fishing boats, of which 76% were under 5 tons and 99.6% (1,975 boats) were under 20 tons. However, of the 298 powered fishing boats of 10–20 tons, 240 belonged to oyster aquaculture management entities, and rather larger boats are used in oyster aquaculture. Aquaculture centres on oysters; the harvest in 2024 was 94,290 tons

(in shell), 63.6% of the national total. Yellowtails and red sea bream, for which antifouling agents for nets are heavily used, were 30 tons and 40 tons (final figures). [S13]

Fishing boats in the Seto Inland Sea are smaller than the national average. In the 2023 Census of Fisheries, the Seto Inland Sea fishery district (a sea-area division used by the Ministry of Agriculture, Forestry and Fisheries, which combines the Seto Inland Sea side of the prefectures facing the Seto Inland Sea) had 12,949 boats, equal to 22.0% of the powered fishing boats nationwide, and the average per boat was about 4.8 tons, a smaller value than the national average of about 8.4 tons (calculated by dividing the total tonnage by the number of boats). [S13]

Hiroshima Prefecture also has many small craft, such as pleasure boats, that are subject to inspection. According to the tabulation of the Japan Craft Inspection Organization (JCI; a body that inspects and registers ships under 20 gross tonnage on behalf of the national government), there were 14,218 small craft subject to inspection registered in Hiroshima Prefecture at the end of March 2026 (about 4.9% of the national total), of which 8,106 were pleasure motorboats, the largest number of any prefecture. Fishing boats used only for fishing within 12 nautical miles and the like are not subject to inspection and so are not included in this number. "Small dual-purpose vessels" (3,233 boats), which are used both for fishing and for other purposes, may overlap with the fishing boats in the Census of Fisheries, so the two numbers cannot be added together. [S30]

The number of people working in fisheries in Hiroshima Prefecture is falling. In the 2023 Census of Fisheries, the prefecture had 1,945 marine fishery management entities (households or companies that engage in fishing or aquaculture for sale) and 2,672 fishery workers (people aged 15 or over who did fishery work at sea on 30 days or more in a year), down 10.0% and 19.7% respectively from 2018. We found no source showing a relationship between this decrease and the burden of biofouling. [S13]

Among the cities and towns in the prefecture, Kure City has the largest numbers of fishery management entities, fishery workers and fishing boats. In the tabulation by city and town of the 2023 Census of Fisheries, Kure City had 634 management entities (about 33% of the prefecture as a whole), 748 fishery workers (about 28%) and 832 fishing boats (about 29%), each the largest number among the cities and towns in the prefecture. However, in the gross tonnage of powered fishing boats, Etajima City (2,353.8 tons) slightly exceeds Kure City (2,345.8 tons). [S13]

Hiroshima Prefecture accounts for most of the ship repair in the Chugoku region. According to preliminary figures from the Chugoku District Transport Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, 1,776 ships in service (ships that are in operation) were repaired in Hiroshima Prefecture in fiscal 2025, with a repair value of 56.37 billion yen, which was about 75% of the number of ships and about 85% of the value for the 5 prefectures of the Chugoku region (excluding western Yamaguchi Prefecture). There is no breakdown of the content of the repairs, and the share for bottom cleaning and painting is not known. These statistics are compiled from the national government's statistical survey of shipbuilding and marine engineering, and for ships not made of steel they include only those of 20 gross tonnage or more or 15 m or more in length, so the repair of many FRP (fibre-reinforced plastic) fishing boats and small craft is not included. The prefecture classification appears to be based on the location of the shipyard that did the repair, but this is not stated in the source. [S31]

Region (Hiroshima and the Seto Inland Sea): biofouling and fuel

The number of organisms settling that become fouling on oysters varies greatly from year to year. The Hiroshima City Agriculture, Forestry and Fisheries Promotion Center surveys every year, on the coast of Hiroshima City and around Etajima Bay and Okurokami Island, the numbers of larvae (the young at the stage when, after hatching from the egg and before settling, they drift and grow in the sea) and of settlement of the Mediterranean mussel, and the numbers of settlement of barnacles and serpulid tube worms (relatives of bristle worms that build

calcareous tubes). The number of Mediterranean mussels settling (the average per survey, with a test rope hung at a water depth of 5 m for about 1 week) varied between 1 and 43 individuals in 2014–2024. 2022 (January to June) was the third highest in the past 10 years, 2023 was the lowest, and 2024 was the second lowest year. [S14]

The settlement of barnacles and serpulid tube worms also varies by year and place. Both are counted by hanging scallop shells at water depths of 1 m and 5 m (barnacles from about August to October, serpulid tube worms until about December at 2 sites). According to the reports, there was no major effect on oyster aquaculture in 2020 and 2022, and settlement increased at some sites in 2023 and 2024 (serpulid tube worms in 2023, barnacles and serpulid tube worms in 2024). For the waters of Kure City, we found no similar published survey. There are no reports of losses in cost or yield. [S14]

The damage records in the prefecture's guidelines also have no item for biofouling. The main damage records in the statistical material of the prefecture's "Hiroshima Oyster Production and Shipment Guidelines" are of three kinds: typhoons, Heterocapsa red tides (a phenomenon in which a type of plankton multiplies and the colour of the sea changes) and shellfish poisoning (a phenomenon in which shellfish accumulate toxins), and the years from 1991 onward are listed. This table also does not list the mass mortality (die-off) of 2025 or the years in which seed oysters (young oysters that are the starting stock for aquaculture) could not be collected well. This does not necessarily mean there was no damage. [S13]

Oyster production in fiscal 2025 fell sharply. According to the prefecture's Fisheries Division, production in fiscal 2025 (July 2025 to June 2026) was 10,100 tons of shucked meat, 60% of the previous fiscal year and 57% of a normal year (the fiscal 2015–2024 average of 17,610 tons). The prefecture attributes the decrease to the mortality (die-off) that occurred throughout the prefecture from September 2025 onward, and does not name fouling organisms as a cause. [S13]

The only case in which fuel was measured in the Seto Inland Sea was one case of a small trawler in Okayama Prefecture. It is a report (not peer-reviewed) in which Okayama Prefecture's fisheries research institute, jointly with the national government's National Research Institute of Fisheries Engineering, fitted a small trawler operating in the sea off western Okayama Prefecture with a device that records distance travelled, engine revolutions and fuel. When the bottom was cleaned and barnacles and algae were removed, fuel use at the same engine speed fell by about 10%. When the engine speed was lowered from 2,500 to 2,300 revolutions per minute, it fell by about 20%, and speed dropped by about 0.4 knots. The number of boats studied, the number of trials, the degree of fouling and the time since the previous cleaning are not stated. [S15]

Region (Hiroshima and the Seto Inland Sea): antifouling active substances

Antifouling active substances (ingredients added to paint and the like to prevent fouling) used in ship-bottom paint have been found in the seawater of the Seto Inland Sea. A paper on oysters in Hiroshima Bay (2022, abstract only checked) detected the antifouling active substance DCOIT in the seawater of the Seto Inland Sea at up to 24 nanograms (ng; one billionth of a gram) per litre. Of the three antifouling active substances studied (diuron, Irgarol and DCOIT), DCOIT was the most toxic to oyster embryos (the earliest stage of development), and for DCOIT the concentration at which no effect appeared on embryos in 24 hours was less than 3 ng per litre. The paper compares, for each substance, the concentration at which no effect appears with the concentration in seawater, and assesses the risk of DCOIT as high and the risk of diuron and Irgarol (up to 27.6 ng and 3.2 ng per litre) as low. Because DCOIT degraded in the samples before analysis (except for samples processed on board the research vessel), its detection rate was low, and the actual concentrations may be underestimated. The time and sites of water sampling are not stated in the abstract. The authors give as the reason for the study that oyster spat have become less likely to settle in Hiroshima Bay in recent years, but they do not show that antifouling active substances are the cause. [S32]

In Hiroshima City's surveys, too, the antifouling active substance diuron was often found, but whether it is increasing is not known. The fiscal 2004 report of the Hiroshima City Institute of Public Health gives the proportion of survey samples from northern Hiroshima Bay in which diuron was found as 32.9% in 2002, 50.0% in 2003 and 52.0% in 2004. The samples are from marinas, fishing ports, environmental standard points in sea areas (water quality monitoring sites) and the like, and the survey sites, number of surveys and seasons differ from year to year. Because the proportion found varies greatly with the season (in 2004, 94.4% in summer and 25.0% in winter), this difference cannot be called a trend of increasing pollution. Concentrations were high in marinas and fishing ports, and the authors consider marinas and fishing ports to be the source. [S33]

There is no measured value for how much antifouling agent for nets is used in Hiroshima Prefecture. The fiscal 2024 estimate of the national government's PRTR (a system that collects and publishes the amounts of chemical substances released, from notifications by businesses and estimates by the national government) puts releases from antifouling agents for fishing nets in Hiroshima Prefecture at about 189 tons. However, this is not a measured value but an estimate made by allocating the national amount used among the prefectures. Most of it is the solvent xylene, which is allocated by the share of the marine aquaculture harvest (12% for Hiroshima Prefecture) and assumed to be released to the air when the nets are coated; it is not a release to the sea. Of the active ingredients, the portion for aquaculture nets is allocated by the harvest of yellowtail and red sea bream aquaculture, and for Hiroshima Prefecture it is set at 0 because the rounded preliminary figure was 0 tons (the final figures are the 30 tons and 40 tons given above). The portion for set nets is allocated by the share of the set-net catch (0.055% for Hiroshima Prefecture), and the active ingredients for Hiroshima Prefecture are put at about 0.16 tons (about 70 kg of disulfiram, about 78 kg of polycarbamate, about 10 kg of copper pyrithione and others), all of which is assumed to be released to the sea. Because most of Hiroshima Prefecture's aquaculture harvest is oysters, it has not been verified whether this allocation matches the actual amount used in the prefecture. [S21, S13]

3. Existing measures, and how they are assessed

Antifouling paint

Antifouling paint (paint that makes it harder for organisms to attach) is the basic means of protecting a ship, and most of it slowly releases a biocide (a substance that weakens organisms and so prevents biofouling). The GloFouling report describes biocide-releasing paints as the most widely used method and one that also has a cost advantage over other methods, and says that the self-polishing type works for up to 5 years. [S2] The IMO guidelines (2023; voluntary guidelines for reducing non-native species) also treat antifouling systems as an effective means of reducing biofouling. [S4]

Most registered antifouling paints contain copper. Of the 363 antifouling methods registered with the Japan Paint Manufacturers Association (as of 23 October 2026), 273 (about 75%) contain cuprous oxide (a copper compound), and there are also 23 methods with no biocide listed (silicone-based ones and others). The counts were made by the researcher from the list of registrations. They are numbers of registrations, including those of overseas companies, and not amounts used. [S16]

One limit is the way the ship is used. On ships that stay still for long periods and on slow ships, biofouling can increase. [S4] The "foul-release coating", which makes fouling come off easily, is said to suit ships that move fast and often, and its performance can fall sharply in recesses and similar areas. [S2] Test results are divided. In a 287-day test cited by GloFouling, barnacles covered up to 75% of a silicone-based foul-release coating, against 4% for a copper-based one. In another test cited by the same report (2006, four commercial paints), the four performed about equally after 60 days of immersion without movement, but only the silicone-based foul-release coating had a small amount of tube-building worms attached. When they were then immersed in a tank

for 15 days under moving conditions, the foul-release coating showed the largest reduction in attached organisms. [S2] In a 12-month test in Washington State (which the state regards as the most severe conditions), two biocide-free products (one of which is said to use a fluorine-containing substance) performed well at four sites, and biocidal paints that contain no copper also showed no difference from copper-based ones. [S17]

Small boats also face another constraint. Copper-based antifouling paint cannot be used on aluminium alloy hulls, because galvanic corrosion occurs. [S8, S26]

Another limit is that the substances go out into the sea. In the seabed of a fishing port in the northern part of Hiroshima Bay, copper of up to 3,300 mg per kg (dry weight) was found in samples from 2004–2005. Core samples were taken, one at each of five sites, and this was in the layer 12–15 cm deep in the one core from the fishing port, not the surface layer (the one core taken at a water quality observation point for the bay [an environmental standard point] had 67–82 mg in every layer). The authors say that paint fragments are highly likely to be the cause. [S18]

Copper-based antifouling paints remain usable for the time being in the EU and the United States as well. The EU extended the approval of cuprous oxide until June 2028, but this is an extension while the review is in progress, not a decision on renewal. [S19] Washington State, too, could not determine that safe and effective alternative paints exist, and did not begin, in 2026, the restriction on copper-based paints for recreational boats that is in state law. The state will examine alternative paints again and report to the legislature by 30 June 2029. [S17] The United States Environmental Protection Agency (EPA), too, in its explanation of the federal standards set in 2024 (standards for the whole country; not yet in application; see chapter 4 for details), does not require alternative paints, on the grounds that there is no direct alternative biocide that is as cheap as copper, or as effective, and that also does not pose similar risks to other organisms. However, among the ships covered by these federal standards (commercial ships of 79 feet [about 24 m] or more in length and others; fishing boats and recreational boats are excluded regardless of size), those that spend 30 days or more a year in waters where the copper concentration exceeds the standard (including ships whose home port is there) are asked to consider copper-free paints or paints with low leaching, according to the type of ship and its operation. [S34]

Hull cleaning, propeller polishing and dry-docking

Cleaning and polishing are measures that reduce fuel use with little effort. The IMO energy-efficiency information page says that in-water hull cleaning reduces total fuel by 1–5% (this varies with the degree of fouling, the ship and the operation; the cost is 5,000–50,000 US dollars per cleaning), and that propeller polishing can reduce main engine fuel by 3–4% (the average annual saving is 0.5–3%; it recommends polishing twice a year, and the cost, for polishing by divers, is 4,000–8,000 US dollars per polishing depending on the number and complexity of the propellers). The method of calculation is not shown. [S20]

The effect of cleaning varies greatly with how the cleaning is done and what it is compared with. In GloFouling's calculation, compared with a bulk carrier 179 m in overall length (14 knots) coated with self-polishing antifouling paint and not cleaned for 5 years, frequent proactive cleaning (cleaning while the fouling is still light) of the hull and propeller reduced fuel costs by 22% (equatorial region, water temperature 25°C) and 18% (Mediterranean, water temperature 17°C), while cleaning of the propeller alone gave about 1%. In the same calculation, cleaning the hull in the third and fourth years reduced fuel by 14% (equatorial region) and 11% (Mediterranean) compared with no cleaning. With no cleaning at all for 5 years, fuel costs were 42% (equatorial region) and 28% (Mediterranean) higher than for a ship that is always clean, but "always clean" is a condition for comparison that the authors themselves describe as ideal but not realistic. Every case assumes the same paint, and the performance of the paint is not analysed. The research costs of this report were paid by members of an industry body made up of paint companies, hull cleaning companies and others (chapter 5). [S2]

An IMO study, in a calculation that assumes 2030 and sets fuel at 375 US dollars per tonne, says that for hull and propeller maintenance the fuel savings exceed the costs. [S1]

Dry-docking is the opportunity to do hull cleaning and repainting together. Antifouling paint is applied when a ship is newly built or at dry-docking, and the IMO guidelines (2023) recommend that the effectiveness of the paint should last longer than the interval between dry-dockings. [S4] Small boats can be hauled out onto land and scrubbed clean. [S8]

The limit of cleaning is its effect on the sea. According to the IMO energy-efficiency information page, many ports do not permit in-water hull cleaning because of the risk of contaminating local aquatic organisms. [S20] On propeller polishing too, the IMO energy-efficiency information page says that there are usually port restrictions because of the risk of contamination by non-native species and algae. [S20] The IMO's 2025 guidance (not mandatory) lists the release of biocides, microplastics and organisms by cleaning, and the shortening of the coating's life through damage to it, and makes it the principle that visible fouling should be removed while being captured. [S4]

Cleaning itself also releases copper from the paint into the sea. There is a study (published in 2014) in San Diego Bay in the United States in which test panels (45 cm square; not a whole ship) coated with two kinds of copper-based paint for recreational boats were immersed in the sea for 106 days and cleaned only once, on day 60, and the release of copper was measured. When 3 years are calculated on the basis of those values (assuming cleaning every 3 weeks in summer and every 4 weeks otherwise), the dissolved copper released at the moment of cleaning was 1–3% of the amount released over the 3 years. However, because cleaning renews the surface of the coating and the leaching afterwards increases, dissolved copper over the 3 years was calculated at 7,084–11,023 micrograms per square centimetre with cleaning, against about 4,160 micrograms (µg; one millionth of a gram) per square centimetre with no cleaning and no movement (which the authors regard as an unrealistic minimum value) (a model calculation based on the measured values, assuming cleaning every 3 weeks in summer and every 4 weeks otherwise). Cleaning with a soft tool gave 26–32% less than a hard pad. The copper during cleaning was in a form more easily taken up by organisms than the normal leaching immediately afterwards. [S35]

The method of cleaning while capturing the removed fouling, in an early evaluation in 2020, removed fouling well, but issues remained with the safety of the effluent. In an evaluation (2020) in which one device was tried in the United States on two government ships that were not in use, the proportion covered by fouling fell by 82–94% on the sides of the hull and the flat bottom. On the other hand, the concentrations of copper and zinc in the effluent after the captured material was treated on land varied by orders of magnitude from test to test, and in one test greatly exceeded the water quality standards. Recesses and similar areas (niche areas; sea chests, rudders and so on) were not evaluated. [S35]

Niche areas are places where, although the area is small, many kinds of organisms attach. In its explanation of the 2024 federal standards, the EPA cites a study which found that, although niche areas are about 10% of the submerged area, more than 80% of the species found in surveys of ship biofouling were there. [S34]

The EPA rates "proactive cleaning", cleaning while the fouling is still light, positively. It treats frequent, gentle cleaning at the slime stage as the best available technology economically achievable (BAT) for limiting the release of organisms and biocides, and says that the fuel savings from keeping fouling at the slime stage exceed the cost of regular cleaning. On the other hand, it also presents a study in which the copper concentration became high directly above the brush during proactive cleaning. [S34]

Monitoring fouling (records of fuel and speed)

Records of fuel and speed are a guide for detecting fouling, but changes often appear with a delay. The IMO guidelines (2023) say, as an example for some ships, that a fall in speed of 1–3% or a rise in fuel of 3–9%

indicates a risk of light fouling, and that a fall in speed of more than 3% or a rise in fuel of more than 9% indicates a high risk of fouling. This is an example taken from the international standard ISO 19030-2 (2016), and is not a criterion that applies to all ships. The same guidelines say that this monitoring is an indicator that often appears with a delay and can also be affected by other factors, that it is mainly for the hull, and that it does not easily capture fouling in niche areas. [S4]

The IMO guidelines also recommend records and direct in-water inspections. They recommend that ships of every type have a ship-specific biofouling management plan and record book, and say that the record book is to be kept on board for as long as the ship is in service. They recommend that in-water inspections be carried out at least every 12–18 months. Ships whose performance is not monitored through fuel and the like have their first inspection within 12 months of the application of the antifouling paint or similar. Ships whose performance is monitored, and whose antifouling paint or similar is found to be working well enough, can put off the first inspection until 18 months after application (however, monitoring may not reveal fouling in niche areas). Areas with neither an antifouling measure nor any other measure are inspected at intervals shorter than 12 months, and when heavy fouling is found and failure of the antifouling is suspected, inspections are increased, for example to twice a year, until dry-docking. All of these are recommendations, not obligations. The same guidelines also say that they may not apply to ships that operate only within the same waters in which the fouling grew. In such operation there is no risk of bringing in non-native species, but measures to avoid releasing harmful substances during cleaning may, they say, still apply. For recreational boats of less than 24 m in length, there is separate guidance based on these guidelines. [S4]

Cleaning of fishing nets, and antifouling agents

Antifouling agents for nets work, but not for long. The effectiveness of an antifouling coating is said to be 3–6 months [S2], and in Norway even coated nets need 15 washes in 18 months, and their direct cost is estimated to be higher than that of uncoated nets (25 washes). [S5] According to review articles and other sources, a copper coating protects a net for up to 7 months, but in seas with heavy fouling it can stop working in 8 weeks, and it rarely works throughout the sea-phase rearing of salmon (usually 10–24 months). [S12, S5] Copper alloy nets last up to 60 months but are very expensive, and foul-release coatings are said to be too expensive for nets. [S2]

For nets that use copper, there are also results showing that the fish grew better. According to a review article, in nets with a copper coating the growth and feed efficiency of sea bass (a relative of the Japanese sea bass) were better than in uncoated nets (one study), and in copper alloy nets they were equal to or better than in nets with a copper coating. [S12]

The assessment of copper leaching from copper alloy nets differs between sources. According to review articles and other sources, copper leaching from copper alloy nets is greater than from a copper coating for the first 6 months in the sea, becomes about the same after that, and is expected to be less over the whole rearing period because less cleaning is needed. [S12, S5] On the other hand, the GloFouling aquaculture guidance says in a table that copper alloy nets release more over time and says in the main text that they release less overall, so the same document contradicts itself. [S2]

Measures for nets also have effects on the sea and on the fish. In the national PRTR (estimates of releases of chemical substances), the substances used on nets in 2024 were 165 tonnes of disulfiram, 142 tonnes of polycarbamate (set nets), 66 tonnes of copper pyrithione and others, and the whole of the approximately 4,000 tonnes of the solvent xylene is assumed to be released to the air. [S21] According to a review article (Bannister et al., 2019), when nets are washed in the water, fragments of the removed fouling (hydroids and others) can damage the gills of the fish. In addition, in parts of two Canadian provinces that have sea areas where the seabed is low in oxygen, in-water washing was stopped (the review article gives no source for this point). On the other hand, copper in the fish that are shipped is said to be below the food standards. [S12]

In Norway, the amount of copper used on nets has changed greatly. According to figures compiled by the Norwegian Environment Agency, the copper used for antifouling of aquaculture nets fell from 1,698 tonnes in 2019 to 306 tonnes in 2023, and then rose to 564 tonnes in 2024 and 578.5 tonnes in 2025 (these are registered amounts used, not measured values of release to the sea). Tralopyril (a fluorine-containing biocide), which is used in place of copper, rose from 53 tonnes in 2019 to 116 tonnes in 2023, and was 108 tonnes in 2024 and 158 tonnes in 2025. [S36]

The Norwegian Institute of Marine Research sees the risk to the marine environment from copper on nets as "moderate" in some sea areas. Its 2026 risk report, as in the previous year, rated this risk "moderate" in three production areas (the divisions of sea area by which aquaculture is managed) and "low" in the other areas. [S36]

The assessment of tralopyril, the substitute for copper, is not yet settled. The same report says that, although tralopyril has a short half-life in the sea of about 9–16 hours, it is a substance that can fall under PFAS (a group of organic fluorine compounds) by the definition of the OECD (Organisation for Economic Co-operation and Development), and that TFA (trifluoroacetic acid), which does not break down any further, can be formed. The manufacturer explains that in seawater it becomes fluoride, not TFA. On the other hand, the report says that a new survey found a strong correlation between the concentrations of TFA and tralopyril, and that because a very small part may be becoming TFA, follow-up is needed. It also writes that tralopyril can accumulate at high concentrations in mussels growing on treated nets, and says that more knowledge is needed. The previous year's report, for 2025, said that the way tralopyril is approved should be questioned, but this statement is not in the 2026 edition. On the other hand, the Norwegian Environment Agency says that tralopyril breaks down relatively quickly and that the risk of it becoming more concentrated through the food chain is small. [S36]

In Japan, among antifouling agents for nets, organotin compounds (a group of substances containing tin, formerly used for antifouling of nets and ships) are regulated by law, and the choice and use of today's antifouling agents is managed, for aquaculture nets, mainly through notices and voluntary schemes. Organotin compounds are regulated under the Chemical Substances Control Law (a law that regulates the examination, manufacture and so on of chemical substances), and fishing nets and antifouling paints containing one of them, TBTO, cannot be imported. In 2003 the Fisheries Agency, in a notice setting out the operation of the basic policy under the Sustainable Aquaculture Production Assurance Act, called for the continuation of examination, certification and registration by national bodies, and for watching by fishery cooperatives and their federations, including over distribution, so that materials whose ingredients or effects are not known are not used (later amendments not checked). The voluntary certification scheme of Wakayama Prefecture (a scheme in which the prefecture certifies; it covers only those red sea bream, bluefin tuna and longtooth grouper farms that obtain certification) makes it a condition to use antifouling agents for nets that have been certified by the "Fishing Net Antifouling Agent Safety Evaluation Committee" and registered with the National Federation of Fisheries Co-operative Associations, and to record the date of treatment, the product and so on. [S22] For antifouling agents for set nets, we found no such scheme.

Antifouling agents for nets containing organotin were once made in large quantities; in the 1980s the industry decided to stop, and they were also regulated by law. A written answer by the government in 1982 puts domestic production of antifouling agents for fishing nets in 1981 at about 5,200 tonnes (an estimate of the amount of product, including solvents and so on), and says that most of it is thought to have contained organotin compounds (TBTO and others). [S37] According to a 1995 report by Kanagawa Prefecture, the Fisheries Agency issued a notice in 1972 to refrain from using organotin antifouling agents for nets, and in 1986 issued a notice confirming it. JF Zengyoren (National Federation of Fisheries Co-operative Associations) agreed in 1985 to halve use, and in 1987, together with the national association of marine fish farmers (Zenkoku Kansui Yogyo Kyokai), decided to stop use completely (the documents of the decision themselves have not been found). [S38] Under the Chemical Substances Control Law, 13 tributyltin compounds and 7 triphenyltin compounds became subject to monitoring in fiscal 1988, and in 1989–1990 TBTO was designated a Class I Specified Chemical Substance and

the other 20 substances Class II Specified Chemical Substances (both are categories under the Chemical Substances Control Law that regulate manufacture and ways of use). [S37]

For rigid gear other than nets, there is a case in which a paint that makes fouling come off easily reduced the work. In a trial calculation by Ishikawa Prefecture, cleaning to remove fouling from the containers used in the aquaculture of the egg cockle (torigai) (a kind of bivalve) took an average aquaculture operator (on the scale of rearing 10,000 seed [the young shellfish from which the farmed ones are grown]) 210 hours a year. When a commercial silicone-based foul-release paint was applied, the effect lasted more than 10 months in one test, and during that time the conventional cleaning was not needed. By replacing the cleaning (210 hours a year) with painting (120 hours, about 570 yen per container), working time was expected to be reduced by more than 40%. However, barnacles attached in the recesses in the bottom of the containers, and no effect was seen on the net lids or the ropes. This is a trial calculation based on one test, on rigid containers and not on nets. [S27]

Measures in the region (Hiroshima and the Seto Inland Sea)

For oysters in Hiroshima Bay, guidance on avoiding fouling is given. On the basis of surveys of larvae and of fouling, the Hiroshima City Agriculture, Forestry and Fisheries Promotion Center guides aquaculture operators in ways of avoiding fouling, such as growing the oysters hung deeper, from the time when the larvae or fouling of the Mediterranean mussel begin to increase (mid-January in 2022, early May in 2024). When fouling by barnacles and serpulid tube worms increased (2023 and 2024), it called for care when moving the rafts and in the work of hanging oysters in shell. The cost of this method and the size of its effect are not known from the published materials. [S14]

4. What is changing

Regulation related to biofouling is moving on three fronts: fuel and emissions, non-native species, and chemical substances. On fuel and emissions, obligations for large ships have already begun, but many of the moves to tighten the rules on non-native species and chemical substances are voluntary or still at the proposal stage, and there are cases, such as copper-based antifouling agents, where a deadline has been extended (as of 1 November 2026).

Fuel and emissions

The obligations on fuel and emissions mainly cover large ships, such as those of 5,000 gross tonnage (GT) or more. The international scheme and the EU schemes that have already begun do not include fishing boats. The domestic criteria ask transport operators to make efforts.

- January 2023: Starting with operation in 2023, a scheme begins under which the CII (an indicator showing how much CO2 a ship emitted per amount of cargo carried and distance travelled in one year of operation) is calculated and rated on five levels from A to E (through an amendment to the MARPOL Convention, which prevents pollution from ships; it entered into force in November 2022). It covers cargo ships of 5,000 GT or more and some passenger ships such as cruise ships, and does not include fishing boats regardless of size. The scheme also does not apply to ships that sail only within the waters of the state where they are registered (for a Japanese ship, ships that sail only within Japan) (parties to the Convention are said to be required to take appropriate measures so that such ships also follow the rules as far as they can). [S24]
- March 2023 (latest revision): The national public notice "Criteria for judgment by freight transport operators", based on the Act on Rationalizing Energy Use (Act on Rationalization of Energy Use and Shift to Non-fossil Energy), asks operators, for ships, to make efforts to carry out inspection and maintenance such as hull bottom cleaning and propeller polishing (this is an obligation to make efforts, and there is no penalty for not

cleaning). The target is to lower energy use per amount transported by an annual average of 1% or more over the medium to long term, and it also lists the introduction of "low-friction hull bottom paint", which holds down fuel use. The criteria for passenger transport operators have the same items. It covers domestic transport, and operators whose ships used for the business have a combined gross tonnage (total fleet tonnage) of 20,000 GT or more submit a medium- to long-term plan and an annual report. Because fishing is not a transport business, fishing boats can be read as being outside its scope (this paper's reading). [S39]

- January 2024: The EU Emissions Trading System (EU ETS; a mechanism that sets a cap on total emissions and requires an emission allowance to be surrendered for each tonne emitted) is extended to shipping. It covers the emissions of cargo ships and passenger ships of 5,000 GT or more that enter EU ports, regardless of flag (and offshore ships as well from 2027): the full amount for voyages between EU ports and within ports, and half for voyages to and from places outside the EU. The share for which allowances must be surrendered is 40% for emissions in 2024, 70% for 2025, and 100% from 2026 emissions onward. It covers CO2 only until 2025, and methane and nitrous oxide are added from 2026. Fishing boats are outside the scope of emissions monitoring and reporting. [S40]
- January 2025: FuelEU Maritime (the EU regulation on ships' fuel) applies in full. It requires passenger ships and cargo ships of over 5,000 GT that call at EU ports to lower the greenhouse gas intensity of the energy used on board (emissions per unit of energy, from production of the fuel to its combustion on the ship) below the 2020 average by 2% in 2025, 6% in 2030 and 80% in 2050. Ships for catching fish or processing fish are outside its scope. [S41] The Q&A of the responsible department of the European Commission (a non-binding explanation) states that energy-saving technology alone does not lower this intensity. [S42]
- April 2025: The IMO adds the values for 2027–2030, which had not been decided until then, to the rates by which the CII standard (the required CII) is lowered from the 2019 reference line (13.625% in 2027, 21.5% in 2030. The values from 5% in 2023 to 11% in 2026 had already been decided in the 2021 guidelines [MEPC.338(76)]. Amendment of the guidelines: MEPC.400(83)). If CO2 per cargo and distance stays the same, the rating can fall year by year (this paper's interpretation). [S24]
- April and October 2025: The draft of the IMO Net-Zero Framework (a mechanism that combines a standard for the greenhouse gas intensity of fuel with a charge on emissions) was approved in April, but its adoption was postponed for one year at the extraordinary session in October. As of 1 November 2026 it has not been adopted, and the session is scheduled to resume on 4 December 2026 (on condition of confirmation at the Marine Environment Protection Committee [MEPC 85] of 30 November to 3 December). The draft covers ships of 5,000 GT or more on international voyages, and sets the price of the "remedial units" that make up the shortfall against the targets in the 2028–2030 reporting periods at, per tonne converted to CO2, 100 US dollars for the first tier and 380 US dollars for the second tier (the start from 2028 assumed adoption in October 2025). [S43]
- July 2026: The European Commission puts forward a proposed amendment to extend the scope of the EU ETS to some ships of 400–5,000 GT. It does not include ships of less than 400 GT, and an option to add all small ships, including fishing boats, was considered but not chosen. As of 1 November 2026 it is a proposal. [S40]

Non-native species

The regulation of biofouling itself is meant to keep out non-native species, and some countries have already made it mandatory, but an international obligation is still being worked on.

- 2017–2022: California (reporting from October 2017 for ships of 300 gross register tons or more that enter the state's ports and can carry ballast water [water loaded to keep a ship stable]; the management plan and record book apply from ships delivered in or after 2018 and ships that completed their first regular dry-docking in or after 2018), New Zealand (a "clean hull" standard from 2018) and Australia (reporting of

biofouling before port entry from 15 June 2022) made biofouling management or reporting mandatory one after another. [S23]

- July 2023: The IMO adopts the biofouling management guidelines (voluntary. They cover all types of ships, but state that they may not be relevant to ships that operate only within the same waters in which the biofouling grew). [S4]
- October 2024: The US EPA sets federal standards for discharges from ships (based on the Vessel Incidental Discharge Act [VIDA]). They prohibit in-water cleaning without capture that releases large fouling organisms (such as barnacles), and require, among other things, proactive cleaning at the slime stage. However, they do not apply until the Coast Guard's implementing regulations are finalised, and as far as this paper has confirmed, as of 1 November 2026 those regulations have not appeared in the US official gazette. They cover, among others, commercial ships of 79 feet (about 24 m) or more in length in US waters, and fishing boats, regardless of size, are outside the scope except for ballast water. Once they start to apply, some state rules will be replaced. [S34]
- April 2025: The IMO approves guidance on cleaning biofouling from ships in the water (MEPC.1/Circ.918) (not mandatory). [S4]
- May 2026: The IMO agrees to develop a legally binding, stand-alone international instrument that makes biofouling management mandatory. The scope of consideration also includes responding to the risk of harmful substances and microplastics being released (the effects on air pollution, greenhouse gases and underwater noise are also considered), and substances released by paint and by cleaning could also be covered (this paper's reading). The target for the final draft is 2029, and the timing of adoption and entry into force is undecided. [S24]

Chemical substances

In the regulation of antifouling active substances, the banning of substances judged harmful and the review of the substances now in use are going forward side by side.

- September 2008: The AFS Convention (the convention that regulates harmful antifouling systems) enters into force and bans organotin. It covers the ships of parties to the Convention and all ships that enter the ports, shipyards and offshore facilities of parties to the Convention. [S4]
- January 2023: New application of the antifouling agent cybutryne is prohibited for all ships (the June 2021 amendment MEPC.331(76). Japan also brought it into effect through Article 65 of the Ordinance for Enforcement). Ships that have cybutryne in their outer coating on 1 January 2023 must, at the next scheduled recoating (within 60 months of the last application of an antifouling system containing cybutryne), remove it or cover it with a sealing coat. Fixed and floating facilities built before 2023 and not dry-docked since, ships that do not make international voyages, and ships of less than 400 GT on international voyages that are accepted by the coastal state are outside the scope of this removal obligation. [S4, S9]
- September 2025: The EU extends the approval expiry date of cuprous oxide to June 2028 (under review). [S19]
- March 2026: On the proposed restriction of PFAS (a group of organofluorine compounds) submitted by five countries under REACH (the EU regulation on chemical substances), the Committee for Risk Assessment (RAC) of ECHA (the European Chemicals Agency) gives its final opinion on 2 March (in support, with derogations). The final opinion of the other committee, the Committee for Socio-economic Analysis (SEAC), is scheduled to be adopted at its meeting of 17–19 November (provisional draft agenda. ECHA says by the end of the year), and the schedule for the European Commission's proposal and the vote by member states is undecided. [S19] The definition of PFAS in the proposal follows the definition the OECD set out in 2021: substances that have one or more fully fluorinated carbons (CF3- or CF2-), and it also includes fluoropolymers (plastics that contain fluorine). [S19] Active substances of biocides handled under the EU Biocidal Products Regulation are excluded without a time limit. However, this exclusion is only for active

substances, and does not include the fluoropolymer binder (the resin that forms the paint film) of a paint. The summary of the proposal does not name antifouling paints for ships or foul-release coatings. [S19]

These regulations extend not only to paint but also to "surface treatment". The IMO guidelines (2023) define an anti-fouling system as something that controls or prevents the attachment of organisms by any of a coating, a paint, a surface treatment, a surface or a device. [S4] The Ordinance for Enforcement of the Ship Safety Act, which implements the AFS Convention in Japan, also includes surface treatment in antifouling systems. When a ship of 400 tons or more (international gross tonnage) that makes international voyages changes or renews its antifouling system, an occasional inspection (an inspection taken separately from the regular inspections) is required. Cases that meet the requirements of the public notice, such as where the area is small, are excepted. [S9]

5. What is not yet known

Where there are no figures

- For the costs caused by biofouling (cleaning, dry-docking and repainting, replacing nets, removing fouling from oysters, extra fuel), the only official figures we found in Japan are a trial calculation for egg cockle (torigai) aquaculture in Ishikawa Prefecture (for an average farmer [10,000 seed], 210 hours a year of cleaning to remove fouling from the containers; these are rigid containers, not nets, and the figure is in hours, not money) [S27] and old examples from oyster aquaculture. The oyster examples are the cost of the work per raft in a 1973 guidance document of Hiroshima Prefecture, and the hours of work in a 2006 guidance document of Kyoto Prefecture on rock oysters (iwagaki). For losses rather than costs, there is an estimate from 1969, when there was a mass outbreak of fouling organisms in Hiroshima Bay. None of these is a present-day value (the details and sources are in chapters 3 and 5 of R3-2). Measured fuel data for small fishing boats are also limited, in the Seto Inland Sea, to a single example from Okayama Prefecture, and the number of boats and the degree of fouling are unknown. [S15]
- We found no statistics on the cost of dry-docking and repainting the hull bottom, or on how often, and at what cost, small fishing boats that are outside the scope of inspection are hauled ashore for cleaning and painting. There are statistics on repair costs (fishery management across Japan, and the value of repair work in the Chugoku region), but the share due to biofouling is not separated out, and the Chugoku region statistics do not include many FRP fishing boats and small vessels. [S29, S31]
- We found no statistics, for Japan as a whole or for Hiroshima, on how often nets are cleaned and replaced or on the hours of work. The values for Japan are old, like the trial in Sagami Bay about 30 years ago (chapter 2). [S6]
- We found no present-day values for copper in the seawater or the seabed of Hiroshima Bay and the Seto Inland Sea. The amount of copper used on nets in Japan is also not known, because cuprous oxide is outside the scope of the PRTR. [S21] We also found no example of a prefectural regulation that makes antifouling agents for nets mandatory. All we found was a voluntary certification in Wakayama Prefecture, and we could not confirm in which organisation the "Fishing Net Antifouling Agent Safety Evaluation Committee" that carries out the review is placed, or whether the Japan Fisheries Resource Conservation Association is involved. [S22]
- For measurements of antifouling active substances (other than copper) in the seawater of Hiroshima Bay, all we found were a survey by Hiroshima City in 2002–2005 and the values in a paper on the Seto Inland Sea whose abstract does not state the time and locations of the water sampling; the present state is not known. [S33, S32]

Where the figures disagree

- The GloFouling report on fuel has values that disagree within the same report. The text of the summary says that a slime layer 0.5 mm thick covering up to 50% of the hull can increase emissions by 25–30%, while the figure on the same page says "up to 25%". In addition, Figure 1 gives 25% for the example of a bulk carrier 175 m long and 55% for the example of a 320 m tanker, but the table in the appendix gives 29.0% and 61%. [S2]
- The IMO calculation assumes a uniform 9% (resistance and fuel) for all ships, while under another method introduced in the same study the power of the main engine increases by 7% on average (2–11% depending on the age of the ship and its maintenance). These are different kinds of quantity and cannot be compared directly. [S1]
- Power and fuel do not necessarily increase in the same way. In the calculation for a gas turbine destroyer, even though power increases by 18% at 15 knots, annual fuel, including the distribution of speeds, increases by 10.3%. GloFouling assumes that fuel is proportional to power. [S7, S2]
- The effect of in-water cleaning is 1–5% of total fuel on the IMO page, and about 9% after cleaning in measurements on 8 tankers. For propellers, the IMO page gives 3–4% from polishing (0.5–3% as an annual average), and the GloFouling calculation over 5 years gives about 1% from cleaning the propeller alone. What is being compared against, and the methods, are different. [S20, S3, S2]
- The cost of biofouling that is often quoted for aquaculture, "5–10% of production costs", is an early estimate from 2004 by an EU research project (in a trade journal); the original denominator is the production value of European aquaculture, and the method of calculation is unknown. [S25, S12] One major Norwegian company puts the cost of preventing and removing fouling at about 2.2% of the production cost of a farm (the company's claim as introduced in a paper). The authors say that indirect costs can greatly exceed this estimate. [S5] The two cannot be compared.
- The share of costs due to biofouling differs greatly depending on what is covered and on the denominator. In the final report (2007; interviews with the several farms that cooperated) of the same research project (CRAB), the cost of washing fish nets in the water with a disc-type cleaner was 0.03–1% of the total cost of the farm, and the method of lifting the nets and drying them was 0.3% (1 site). However, most of the cost of cleaning nets was machine washing on land, and the cost of cleaning nets at 4 fish farms was about 17,000–151,000 euros a year (1.94–4.86 euros per square metre of net). The cost of cleaning shellfish by hand was up to 30% of the total cost. [S44] For the aquaculture of green-lipped mussels (a kind of mussel) in New Zealand, there is an estimate that puts the losses of yield and seed due to fouling by the Mediterranean mussel at 16.4 million US dollars a year, about 10% of the industry's production value (this is as introduced in a review article; we have not checked the original study). [S12]
- The GloFouling guidance on aquaculture (a compilation of the literature) describes, on adjacent pages, the same cost of 1.5 billion–3 billion US dollars a year both as 5–10% of production costs and as 10–15%. This amount was derived from the 5–10% by a review article (Fitridge et al., 2012) and is not an independent estimate. [S2, S12]
- Hiroshima Prefecture's share of oysters in Japan is 63.6% in the national in-shell statistics (2024), and 65.3% in the prefecture's estimate, which converts the national statistics to the weight of shucked meat. Because the basis of weight differs, the basis needs to be stated when the two are placed side by side. [S13]

Data that are unfavourable to new approaches

- The existing measures work (chapter 3). In the calculation for a destroyer, the penalty of a freshly applied coating is small, at about 1.4% (about 2% in required power in the calculation for a frigate), and for a new surface to make a difference in fuel, it needs to keep a clean state for longer. [S7]

- The size of the effect on small boats is unknown. In the one example from the Seto Inland Sea, fuel fell by about 10% with cleaning and by about 20% when the engine speed was lowered (speed falls by about 0.4 knots), but few of the conditions are recorded, and the two can also be used together, so this cannot be used to compare which is better. [S15]
- Foul-release coatings are said to be best suited to ships that are fast and move often, and their performance can fall greatly in areas such as recesses (chapter 3). As weaknesses of foul-release coatings, Washington State cites fouling while the vessel is stationary and the weakness of the coating film, and they are also said to be too expensive for nets. Foul-release paints that are said to use fluorine-containing substances are also already on the market. [S2, S17] Regarding biocide-free paints of the self-polishing type (the type whose surface dissolves little by little), the same state says that they have not yet reached practical use in terms of technology and cost. [S17]
- The EU's proposed PFAS restriction places fluoropolymers, and coatings in the transport sector including ships, within the scope of its evaluation. There is also an option of continued use under conditions, and how antifouling coatings for ships will be treated is not known. [S19] Washington State says that the silicone and fluorine-based substances in biocide-free paints may also be hazardous. [S17]
- In Hiroshima, biofouling is not an official category of damage, and there is also very little fish aquaculture, which uses large amounts of antifouling agents for nets. Production of Hiroshima oysters in fiscal 2025 was 57% of a normal year, and the provisional opinion of the prefecture's expert panel cites factors such as the prolonged period of high water temperature, and does not cite fouling organisms (the final opinion is due in March 2027). [S13]
- The main sources have interests at stake. The GloFouling report on fuel is a joint report with the industry body GIA (Global Industry Alliance for Marine Biosafety), and the cost of the study was paid by GIA members, including paint, hull cleaning and ultrasonic companies and one shipping company. For the in-water cleaning value (1–5%) on the IMO information page, from 2016 until at least December 2024 the only reference was a single brochure from a cleaning company (confirmed from archived past versions of the page; it has now been replaced). [S2, S20]

Reliability and the publisher's position

The greatest uncertainty is that calculations for large, fast ships cannot be applied as they are to the boats of under 5 tonnes in Hiroshima. The direction, that fuel increases, is the same in calculations and in measurements, but the size relies in large part on calculations by the same research group, and the examples measured on actual vessels are few. For fuel, they are 8 tankers (abstract only checked), one example of a small bottom trawl fishing boat in Okayama Prefecture (the number of boats is not stated) and 1 small fishing boat in Sri Lanka; for speed, measurements carried out in fiscal 2009, 2012 and 2013 on 1 training ship of Nagasaki University (155 gross tonnage, about 43 m in overall length, made of aluminium alloy; measured in the Goto-nada Sea in Nagasaki Prefecture) (even with the same paint, the results differ greatly from year to year); and for power, 2 frigates of the US Navy (the increases due to fouling were measured as 9% and 24%). [S3, S15, S8, S26, S7] The GloFouling report and many later calculations use the fouling categories and roughness values of Schultz (2007), and are not confirmations that are independent of one another. The 25–30% of GloFouling is based only on computer calculations of water flow by one research group. [S7, S2]

We checked the dates and provisions of regulations against the original texts as far as possible, but the future schedules for the EU's PFAS restriction and for the IMO are provisional plans or targets, and it has not been decided when the US federal standards will apply.

The publisher of this paper (SeatecHIROSHIMA Ltd.) runs a business that controls biofouling by surface treatment of materials, and is in a position that may compete with the existing measures covered in this paper. This paper does not cover the company's own technology or results.

6. Sources

We examined materials published up to 1 November 2026. We examined mainly materials from international organisations, from Japan's national, prefectural and city governments, and from EU and national bodies, together with peer-reviewed papers, and we used only figures that a separate researcher had checked against the very materials listed as sources (for S3 and S32, the abstract only). Among the figures that review articles and similar works quote from other studies, there are some that we have not checked back to the original study. Some overseas government websites block automated retrieval, and we have not used rules that we could not check. Reliability: A = laws and regulations, resolutions, government materials; B = peer-reviewed papers, public reports that state their method; C = review articles, explanatory materials, industry bodies; D = trade magazines. S1 to S27 have the same numbers as in the first edition. Materials added in the second edition are S28 onwards. S28 to S44 are arranged in the order in which they are first used in the text, and S45 was added later, so its number does not follow the order of the text.

ID	Source (publisher, year)	Type	Reliability	Chapters used
S1	Fourth IMO GHG Study 2020 (IMO, 2020)	Estimate	A	Chapters 1–3, 5
S2	GloFouling: report on fuel consumption and greenhouse gases (jointly with the industry body GIA, funded by GIA members); aquaculture guidance (jointly with IOC-UNESCO, a compilation of the literature) (2022)	Report	B	Chapters 1–3, 5
S3	Adland et al.: the energy-saving effect of periodic hull cleaning (2018, abstract only checked)	Paper	B	Chapters 1, 2, 5
S4	IMO: AFS Convention; amendment banning cybutryne MEPC.331(76) (2021); biofouling management guidelines MEPC.378(80) (2023); guidance on in-water cleaning (2025)	Resolution	A	Chapters 1–4
S5	Bloecher and Floerl: the cost of biofouling management in salmon aquaculture (2021)	Paper	B	Chapters 1–3, 5
S6	Yamamoto: fouling organisms on set nets in Sagami Bay (in Japanese) (Kana - gawa Prefecture, 1996)	Prefecture	B	Chapters 1, 2, 5
S7	Schultz et al.: the economic impact of biofouling on naval vessels (2011); Schultz: effects of coating roughness and biofouling on ship resistance and power (2007)	Paper	B	Chapters 2, 5
S8	Guidance on fuel savings for small fishing vessels (FAO, 2012); newsletter of the Bay of Bengal Programme for fisheries (FAO/BOBP, September 1982)	Guidance	C	Chapters 2, 3, 5
S9	Ordinance for Enforcement of the Ship Safety Act (in Japanese) (e-Gov, version in force from July 2026)	Law	A	Chapters 2, 4
S10	Ships subject to inspection; types of inspection; preparation before a ship in - spection (in Japanese) (Japan Craft Inspection Organization)	Explanatory	C	Chapter 2
S11	Pathways of non-native species: Otani (Japanese Journal of Benthology, 2004) (in Japanese); Bailey et al. (2020)	Paper	B	Chapter 2
S12	Review articles on biofouling in aquaculture: Fitridge et al. (2012); Bannister et al. (2019)	Review article	C	Chapters 2, 3, 5
S13	Hiroshima and the Seto Inland Sea: Census of Fisheries; tables; tables by city and town; fishing boats in the Seto Inland Sea fishing area (Census Table 2-1); production statistics; fish; oyster guidelines; introduction to the oyster guide - lines; statistics in the oyster guidelines (record of damage); expert panel (in Japanese) (Hiroshima Prefecture and Ministry of Agriculture, Forestry and Fisheries, 2025–26)	Statistics	A	Chapters 2, 5

ID	Source (publisher, year)	Type	Reliability	Chapters used
S14	Annual business reports: fiscal 2020 (Reiwa 2); fiscal 2022 (Reiwa 4); fiscal 2023 (Reiwa 5); fiscal 2024 (Reiwa 6) (in Japanese) (Hiroshima City Agriculture, Forestry and Fisheries Promotion Center)	Report	B	Chapters 2, 3
S15	Let us cut fishing costs through energy-saving operation (in Japanese) (Okayama Prefecture, 2016)	Prefecture	C	Chapters 2, 5
S16	List of registered antifouling methods (Japan Paint Manufacturers Association, October 2026)	Industry body	C	Chapter 3
S17	Antifouling paints: third report to the Legislature (Washington State, 2024)	State	A	Chapters 3, 5
S18	Tsunemasa and Yamazaki: antifouling active substances in the seabed of northern Hiroshima Bay (2014)	Paper	B	Chapter 3
S19	EU: Decision 2025/1812; on the PFAS proposal, the ECHA announcement; provisional draft agenda; summary (2025–26)	Law	A	Chapters 3–5
S20	IMO energy-saving information (GreenVoyage2050; prepared with DNV, and it states that IMO does not guarantee the accuracy of the content): Hull cleaning; Propeller polishing (updated April 2026); archived versions of Hull cleaning (2016; December 2024)	Explanatory	C	Chapters 3, 5
S21	PRTR estimate "antifouling agents for fishing nets": estimation method; table of estimation results (in Japanese) (Ministry of the Environment and Ministry of Economy, Trade and Industry, 2026)	Estimate	A	Chapters 2, 3, 5
S22	Management of antifouling agents for nets: Fisheries Agency notice (2003); Wakayama Prefecture's certification scheme (scheme page; certification standards for red sea bream; Pacific bluefin tuna; longtooth grouper); Order for Enforcement of the Chemical Substances Control Law (Articles 1 and 7) (in Japanese)	Notice	A	Chapters 3, 5
S23	Biofouling rules for arriving ships: California, USA; NZ; Australia (2017–21)	Rule	A	Chapter 4
S24	IMO: amendments to Annex VI MEPC.328(76) (2021); CII reduction factors MEPC.400(83) (2025); MEPC 84 report; Add.3 (2026)	Convention	A	Chapter 4
S25	Lane and Willemsen: the CRAB estimate (trade magazine, 2004)	Magazine	D	Chapter 5
S26	Shimizu et al.: the effect of bottom fouling on the speed and fuel consumption of a medium-sized light-alloy vessel (in Japanese) (The Journal of Japan Institute of Navigation, 2014)	Paper	B	Chapters 3, 5
S27	A labour-saving technique for egg cockle (torigai) aquaculture using silicone paint (in Japanese) (Ishikawa Prefecture, 2021)	Prefecture	C	Chapters 3, 5
S28	Ministry of Land, Infrastructure, Transport and Tourism: on the introduction of a new dry-docking inspection system for domestic passenger ships (in Japanese) (2005; a trial calculation by a study and review committee of the Shipbuilding Research Association of Japan)	Announcement	A	Chapter 2
S29	Ministry of Agriculture, Forestry and Fisheries: results of the 2025 (Reiwa 7) statistical survey on fishery management (2026); explanatory notes on the survey items (in Japanese)	Statistics	A	Chapters 2, 5
S30	Japan Craft Inspection Organization: registered boats at the end of the fiscal year (end of fiscal 2025 (Reiwa 7)); statistical terms (in Japanese) (2026)	Statistics	B	Chapter 2
S31	Ministry of Land, Infrastructure, Transport and Tourism: fiscal 2025 (Reiwa 7) production trends of the ship industry in the Chugoku region (Chugoku District Transport Bureau, 2026, preliminary figures); shipbuilding and marine engineering statistics: outline of the shipbuilding survey (in Japanese)	Statistics	A	Chapters 2, 5

ID	Source (publisher, year)	Type	Reliability	Chapters used
S32	Onduka et al.: the risk of three antifouling active substances to oyster embryos and larvae in Hiroshima Bay (2022, abstract only checked)	Paper	B	Chapters 2, 5
S33	Hiroshima City Institute of Public Health: the state of contamination of northern Hiroshima Bay by ship-bottom antifouling agents that replaced organotins (in Japanese) (Annual Report No. 24, fiscal 2004)	Report	B	Chapters 2, 5
S34	US Environmental Protection Agency: federal standards for discharges incidental to vessels (40 CFR Part 139) (US Federal Register, 2024)	Rule	A	Chapters 3, 4
S35	Effects of in-water cleaning: Earley et al. (2014); Tamburri et al. (2020)	Paper	B	Chapter 3
S36	Norway: Norwegian Environment Agency statistics on antifouling agents for nets (updated 2026); risk reports of the Institute of Marine Research (2026; 2025)	Government	A	Chapter 3
S37	Organotin antifouling agents for nets: written answer of the Cabinet (1982); Ministry of the Environment, "Chemicals in the Environment" (2004) (in Japanese)	Government	A	Chapter 3
S38	Kanagawa Environmental Research Center: survey of the actual state of organotin compound contamination in coastal waters (in Japanese) (Research Report No. 18, 1995)	Prefecture	C	Chapter 3
S39	Act on Rationalizing Energy Use and public notices: standards of judgement for freight carriers (revised 2023); standards of judgement for passenger carriers; explanation by the Ministry of Land, Infrastructure, Transport and Tourism; Act on Rationalizing Energy Use, Articles 103 and 127 (e-Gov) (in Japanese)	Public notice	A	Chapter 4
S40	EU emissions trading: European Commission page; Directive 2023/959; impact assessment of the proposed extension SWD(2026) 616 (2023–26)	Law	A	Chapter 4
S41	FuelEU Maritime: European Commission page; Regulation 2023/1805	Law	A	Chapter 4
S42	The responsible department of the European Commission: Q&A on FuelEU Maritime (not binding)	Explanatory	C	Chapter 4
S43	IMO Net-Zero Framework: draft regulations (Circular Letter No. 5005) (2025); announcements (April 2025; October 2025; May 2026)	Convention	A	Chapter 4
S44	CRAB (an EU research project): final report (CORDIS, 2007; interviews with the aquaculture farms that cooperated)	Report	C	Chapter 5
S45	Ministry of Agriculture, Forestry and Fisheries: results of the 2025 (Reiwa 7) survey on changes in the structure of fisheries (2026, approximate figures from a sample survey); basic data on agriculture, forestry and fisheries (fishery workers) (in Japanese)	Statistics	A	Chapter 2

Related materials: R3-1 Oyster mortality (die-off), R3-2 Fouling organisms on oysters, R3-3 The workforce and manual work of oyster aquaculture, R6 What is changing (why now), R7-A13 Fouling organisms on egg cockle (torigai) aquaculture baskets, R7-C26 Uwa Sea: the decline in the number of places where fishing boats are hauled ashore to have their bottoms cleaned, R7-D16 Fouling on nets that protect nori (laver) from being eaten, I1 List of assessments